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Higgs boson cross section and mass measurements in the $H \to \gamma\gamma$ channel with the CMS experiment(*)

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Summary. — This report presents a review of the measurements of the Higgs boson's mass and production cross-section in the diphoton decay channel using data collected by the CMS experiment at the LHC. The cross-section in a fiducial phase-space was measured in Run 2 with 137 fb^{-1}, obtaining $73.40^{+6.1}_{-5.9}$fb, in agreement with the Standard Model theoretical value. The Higgs boson mass was measured with Run1 and Run 2 2016 data, obtaining 125.78 ± 0.26 GeV. Due to the increased radiation damage in the calorimeters, a finer treatment of systematic uncertainties arising from longitudinal inhomogeneity in the ECAL light collection is necessary for ongoing full Run 2 analyses. Future analyses with data from Run3 are expected to improve precision both on production cross-section and on the Higgs boson's mass.

1. – Introduction

The Higgs boson, an essential element of the Standard Model (SM) of particle physics, was discovered in 2012 by the ATLAS and CMS collaborations at the Large Hadron Collider (LHC) at CERN [1].

This particle is extensively studied by observing its decay products in several channels, for example the four leptons channel from Z decays or the diphoton channel.

In particular, the diphoton Higgs boson decay, forbidden at tree level but allowed with fermions or W loops, has a branching ratio of about 2.3×10^{-3}. Studies of Higgs boson properties in the diphoton channel are made possible by the excellent invariant mass resolution provided by the electromagnetic calorimeter, allowing to efficiently separate the Higgs signal peak from the continuum background due to $\gamma\gamma$, γ+jet and multi-jet events, where at least one jet is misidentified as photon, as shown in fig. 1.

Detailed studies of Higgs boson's properties, such as the production fiducial and differential cross-sections, are crucial for validating the SM and exploring potential new physics beyond the current theoretical framework. The measurement of the mass is also paramount for this program, as production cross-sections and branching ratios depends on its mass, which is also linked, through radiative effects, to other electroweak parameters such as weak angle, Z, W and top quark masses.

In this report, recent and future measurements of Higgs boson's production cross-section and mass in the diphoton channel with the CMS experiment are reviewed.

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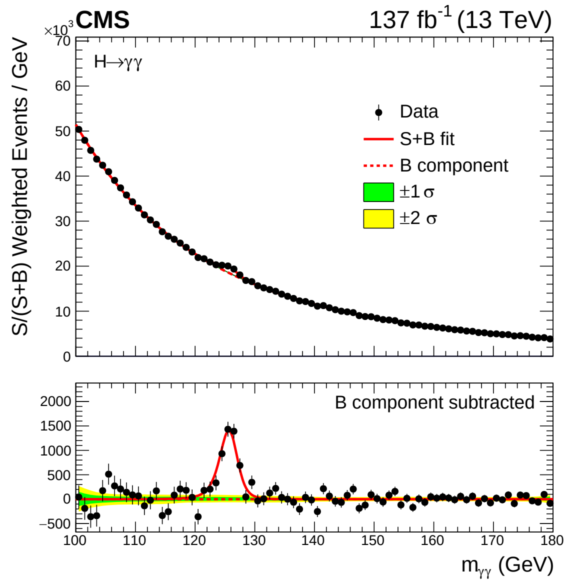


Fig. 1. – Diphoton mass distribution for Higgs boson candidate events in Run 2 [2].

2. – General analysis strategies

The Compact Muon Solenoid (CMS) detector at the LHC is a general-purpose detector designed to investigate a wide range of physics phenomena, including studies for the Higgs boson. The CMS detector features a highly efficient Electromagnetic Calorimeter (ECAL) crucial for detecting photons and measuring their energies with high precision.

In order to measure photon and electrons energies, a first algorithm, the Particle-Flow Clustering, forms clusters out of the crystals hit by a particle interacting with the calorimeter. A second algorithm, referred to as SuperClustering, gathers clusters into super-clusters, to collect the energy of a particle that possibly showered in the material upstream of the ECAL [3].

Key aspects of the ECAL include its excellent energy resolution and precise position measurement capabilities, which are essential for the reconstruction of the diphoton invariant mass, needed for example to find Higgs bosons candidate events. During Run 2 ECAL showed an energy resolution ranging between 1.6% to 5%, generally better in the barrel, for electrons with momentum around 45 GeV arising from $Z \to ee$ decays.

A Boosted Decision Tree (BDT) classifier is used to distinguish between supercluster initiated by photons and by other particles.

Beyond invariant mass discrimination, Higgs boson candidates are selected among diphotons pairs based on several criteria, for instance [2]:

- Pseudorapidity ($|\eta|$): The supercluster of each photon is required to have a pseudorapidity $|\eta| < 2.5$, where the transition region between endcap and barrel is excluded

- Normalized transverse momentum ($p_T/m_{\gamma\gamma}$) of the two photons: leading (subleading) photons $p_T/m_{\gamma\gamma}$ have to be greater than 1/3 (1/4).

Candidate events are divided into categories based on year, mass resolution, diphoton BDT score or production mechanism, depending on the specific analysis.

For each category, signal and background models are constructed:

- Signal Model: a sum of up to four Gaussian functions, derived from simulated signal events
- Background Model: a combination of smoothly decreasing functions, fitted to the data in the mass sidebands

3. – Fiducial cross-section measurement

The fiducial cross-section is measured by interpolating the signal over the background in the predefined fiducial phase space, reflecting the detector acceptance and selection criteria [2]. This is done to build the signal at the generator level, with a selection on generated particles properties which can be well reproduced by reconstructed quantities, in order to get an unfolding matrix, included in the likelihood, as diagonal as possible.

The fiducial phase-space employed is defined by the cuts in $p_T/m_{\gamma\gamma}$ and pseudorapidity described above, and by a cut I_γ, defined as the sum of the energy of all stable hadrons produced in a cone of radius $\Delta R = 0.3$ around the two photons, and the resulting events are split in three analysis categories based on the mass resolution.

The fiducial cross-section measured in Run 2 (13 TeV, 2016-2018) with a 137 fb^{-1} integrated luminosity is $73.40^{+5.4}_{-5.3}(\mathrm{stat})^{+5.4}_{-5.3}(\mathrm{stat})\,\mathrm{fb} = 73.40^{+6.1}_{-5.9}\,\mathrm{fb}$, which is compatible with the theoretical value of 75.4 ± 4.1 fb within the Standard Model, as shown in fig. 2.

Furthermore, a contextual measurement of the cross-section in sub-regions of the fiducial phase space is performed to probe for potential deviations from the SM in particular

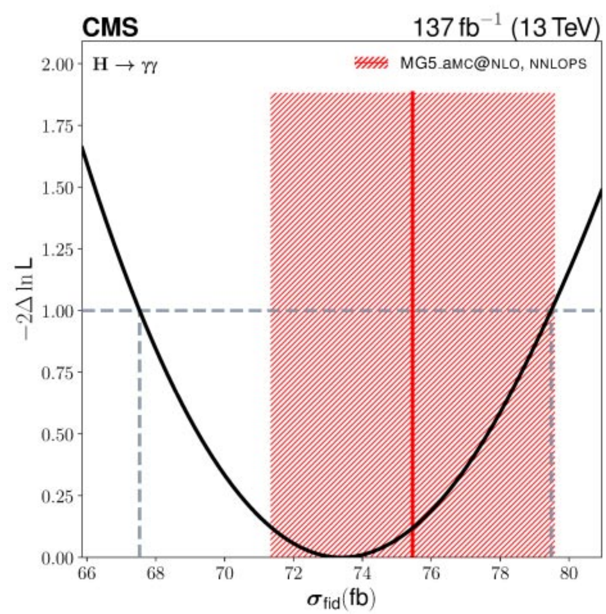


Fig. 2. – Likelihood scan of the fiducial cross-section [2].

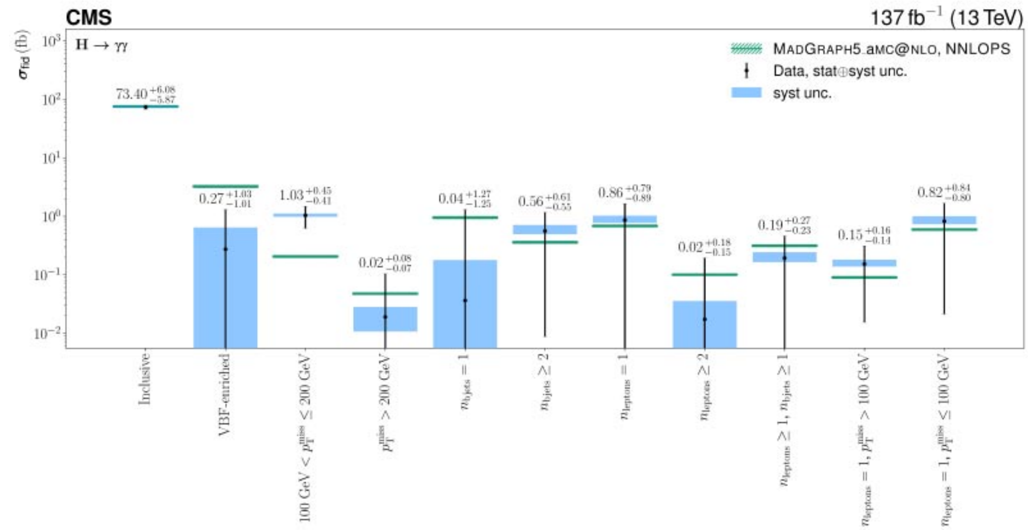


Fig. 3. – $H \to \gamma\gamma$ cross-section in dedicated regions of the fiducial phase space. Their definition at generator level, on top of the fiducial requirements are indicated on the plot [2].

kinematical regimes such as high jet multiplicities and high Higgs boson p_T, as shown in fig. 3.

Future measurements with the Run3 dataset (13.6 TeV, 2022-2025) are expected to achieve a higher precision due to the larger integrated luminosity and improved detector performance.

An increase in the cross-section for the Higgs boson production by 7.5% is foreseen due to the higher center-of-mass proton energy.

4. – Mass measurement

For the mass measurement [4], a multivariate classifier (VBF combined BDT) is trained to distinguish between vector-boson fusion (VBF) Higgs boson production and gluon-gluon fusion (ggH) accompanied by two jets. The VBF events are subdivided into three categories based on the VBF combined BDT score. The remaining events are mostly ggH events and are designated as "untagged". These events are further subdivided into four categories based on their diphoton BDT score, for a total of seven categories with different performances in mass resolution, as shown in fig. 4.

For each category, the template shape of the probability density function used to fit the signal component of data is chosen with Monte Carlo simulations within the systematics, and the template position is left floating to fit m_H.

Combining all categories, the mass of the Higgs boson is measured to be 125.78 ± 0.26 GeV using data from Run1 and 2016, as shown in fig. 5.

Due to the increased radiation damage in the calorimeters, a finer treatment of the dominant systematic uncertainty arising from longitudinal inhomogeneity in the ECAL light collection is necessary for full Run 2 analyses, and will be employed in an ongoing analysis targeting a full Run 2 measurement [5].

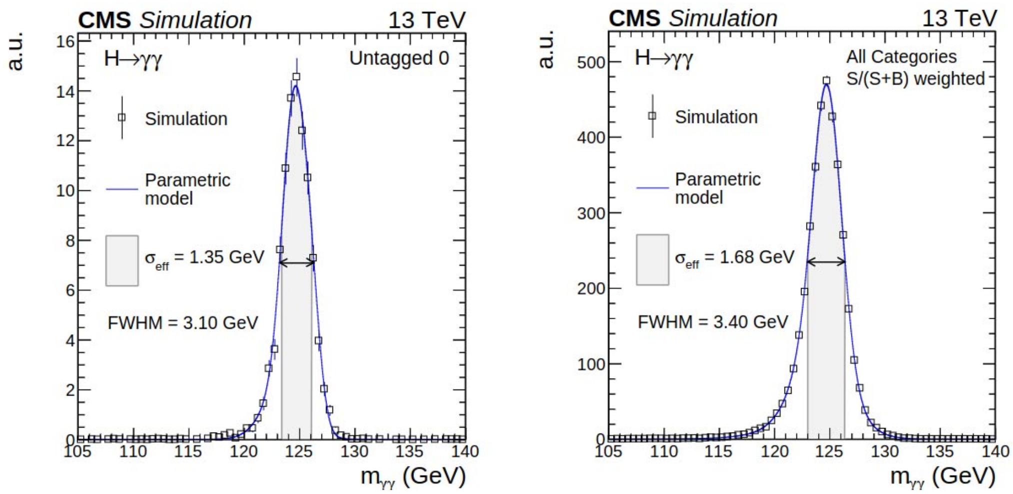
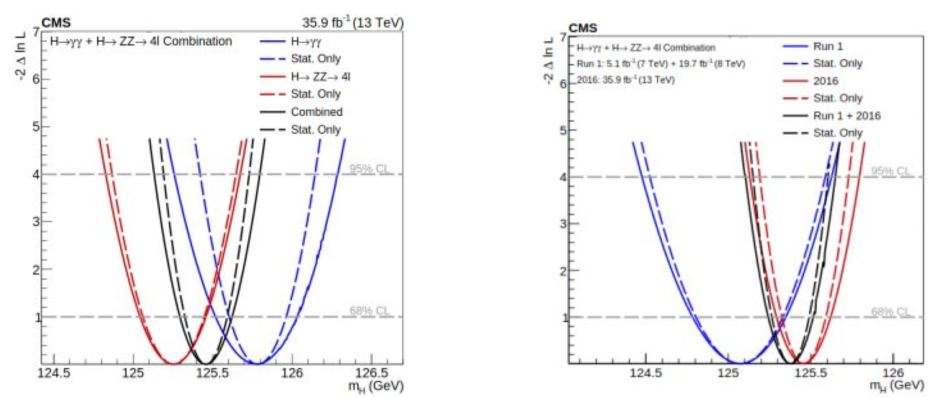


Fig. 4. – Signal shape models for the highest resolution analysis category (left), and the combination of all categories, for a simulated $H \to \gamma\gamma$ signal sample with $m_H = 125$ GeV [4].

5. – Conclusion

Higgs boson's mass and production cross-sections measurements in the diphoton decay channel with the CMS experiment are reviewed. The cross-section in a fiducial phase-space was measured in Run 2 with 137 fb^{-1}, obtaining $73.40^{+6.1}_{-5.9}$ fb, compatible with the Standard Model theoretical value. The Higgs boson mass was measured with Run1 and Run 2 2016 data, obtaining 125.78 ± 0.26 GeV. Future analyses with data from Run3 are expected to improve precision on production cross-section, while an ongoing analysis with full Run 2 datasets will increase precision and on the Higgs boson's mass, with finer treatment of systematic uncertainties arising from crystals non-uniform light collection.



(a) (b)

Fig. 5. – Likelihood scan of the measured Higgs boson mass in the $H \to \gamma\gamma$ and $H \to ZZ \to 4l$ decay channels, shown both individually and in combination. (a) Results with 2016 datasets [4]. (b) Results with Run1+2016 datasets.

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